5. *Theme 3 The 4D Heliosphere: The heliosphere in space and time*

Research Objectives for FY2002-2004 from the Ulysses 2001 Senior Review Proposal

(1) Quantify the evolution of the 3D heliosphere as it transforms to the simpler solar minimum configuration and begin studying cycle-to-cycle variations and variations in the second half of the 22 year Hale magnetic cycle.

(2) Determine if open magnetic flux is invariant and independent of latitude throughout the solar cycle.

(3) Characterize HCS tilt and dynamics as it rotates to lower latitudes.

(4) Extend interstellar H and He density measurements over the solar cycle in an attempt to understand their observed temporal variations.

(5) Establish ionization rates for various interstellar atoms inside the heliosphere over the full solar cycle, as a function of latitude.

Accomplishments in 2001-2003 and Objectives for 2004-2005 and 2006-2007

To define terminology, when the solar wind is time-stationary, the pattern of compression and rarefaction corotates with the Sun, producing CIRs. When the flow evolves on a time scale comparable to or less than a solar rotation period (~25 days) the pattern is not time-stationary and compressions are then known as stream interaction regions (SIRs). Both SIRs and CIRs are commonly bounded by forward and reverse shocks beyond ~2 AU that are sites of charged particle acceleration (e.g. Balogh et al. [1999]).

Evolution of the 3D heliosphere:

Measurements during U-I led to a global view of the solar wind and heliosphere before and near solar minimum in which it is dominated at latitudes above ~30 - 40˚ by high-speed streams emanating from large PCHs (Fig. 1.3) [McComas et al., 2002]. Solar wind variability was largely confined to a band determined by the width of the coronal streamer belt and the tilt of the solar magnetic dipole relative to the solar rotation axis. In the low-latitude region tilted CIRs were the dominant structures, excepting the occasional interplanetary CME (ICME).

CIRs:

Ulysses discovered systematic latitudinal patterns of CIR shocks and flow deflection and opposed meridional tilts in the northern and southern solar hemispheres during the U-I [Gosling and Pizzo, 1999]. Multi-point measurements of CIRs and SIRs are required in and out of the ecliptic plane to fully characterize the tilt. Such measurements will, for the first time, be available using ACE, Wind, STEREO, and Cassini. U-II (Fig. 1.3) is providing a complementary picture of the heliosphere around and following solar maximum, in which SIRs and CMEs are the dominant structures.

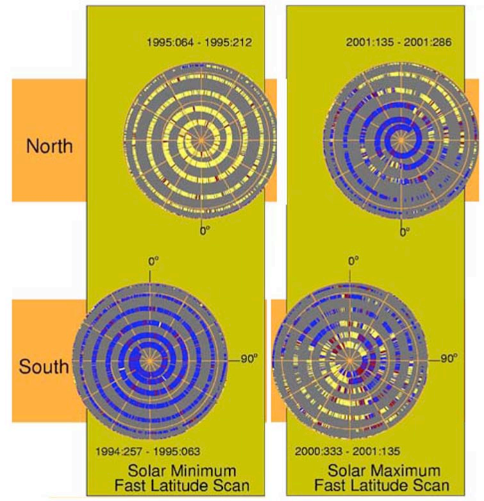

Figure 5.1. Magnetic polarity projected onto spheres representing the solar wind source surface, viewed from above the solar rotational poles. FLS-I is on the left and FLS-II is on the right. Blue (yellow) is negative (positive) polarity. Carrington longitudes 0° and 90° are marked [Jones & Balogh, 2003].

The HCS, the HMF, and the 3D post-maximum heliosphere:

Despite the complexity of the solar wind at solar maximum, the HMF remained relatively well structured – the global magnetic field axis apparently reverses primarily by rotating in latitude. Fig. 5.1 (also Fig. 3.2) illustrates the solar minimum HMF at the mid-point of this rotation [Jones & Balogh, 2003]. Recent data show the HCS returning to lower heliolatitudes, indicating that the dipole and rotational axes are realigning, with reversed magnetic polarity.

Latitudinal magnetic flux distribution:

In 2004-2005, fast wind from the south PCH is unlikely to reach down into the ecliptic but will be continuously observable at Ulysses due to the tilt of the dipole. Ulysses will re-examine the nature of the modest increase in the open magnetic flux, $r^2 B_r$, at mid-latitudes seen in U-I. This increase may be related to the "flux deficit" observed at low latitudes by Pioneer 10-11 that may be a consequence of excess solar wind pressure pushing magnetic flux away from the equator. Observations of the mid-latitude increase require that the spacecraft be above the CIR zone. HMF observations in 2005-2007 will measure the mid-latitude increases during solar minimum when they are easiest to detect.

Broken north-south symmetry:

During U-I, Ulysses discovered an unexpected north-south (N-S) heliospheric asymmetry in most Ulysses data sets. The simplest manifestations of the N-S asymmetry are an offset of the heliomagnetic from the heliographic equator, a latitude offset of -10° in the galactic and anomalous cosmic ray fluxes, and hemispheric differences in the solar wind speed and heavy ion fluxes [Smith, et al., 2000; Simpson et al, 1996; Gloeckler et al., 2002]. Negative polarity magnetic fields at southern latitudes filled a smaller volume of the heliosphere than positive northern polarity magnetic fields. Is this spatial asymmetry intrinsic to solar magnetic fields, a function of the Hale cycle, or merely random? There are essentially permanent longitudinal asymmetries in the solar magnetic field [Neugebauer et al., 2000] so it is not necessarily contradictory that there be a north-south asymmetry. However, it is not a component of standard solar dynamo models. A single orbit showing the N-S asymmetry is insufficient to suggest a cause. Ulysses is poised for another orbit that will help understand the persistence of the asymmetry and perhaps an important new aspect of the solar dynamo.

The N-S asymmetry and solar wind mechanisms/models:

The N-S asymmetry in solar wind heavy ion fluxes implies a connection between the global nature of solar magnetic field and the formation of solar wind. It had been assumed that the HMF, the solar wind, and energetic particles are loosely coupled. Observations by Ulysses [von Steiger et al., 2000] and in-ecliptic spacecraft in *UFC*-FLS will help establish the character of the relationship between solar wind speed and magnetic field and the importance of the asymmetry in galactic and anomalous cosmic rays and interstellar dust. Detection of an asymmetry is feasible only during the fast latitude scan since only then is the time required to make a full latitude scan comparable to or less than the characteristic time for significant changes in the solar cycle modulation. At solar maximum, conditions were too dynamic to allow any asymmetry to be measured. In 2006-2007 the Sun will again be near solar minimum conditions.

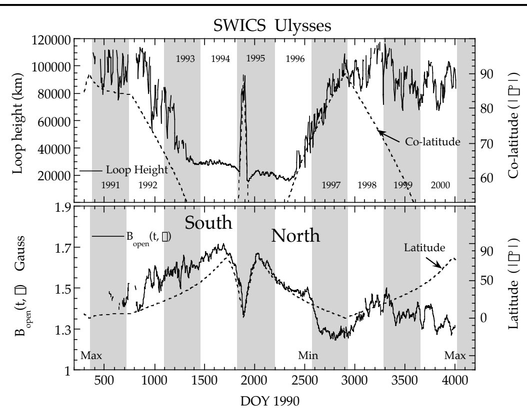

Figure 5.2. Top: Computed loop height (solid curve) and absolute value of the co-latitude of Ulysses (dashed curve). Bottom: Open magnetic field strength near the Sun (solid curve) and absolute value of the latitude (dashed curve), all vs. DOY 1990 (odd years are indicated by shaded regions) for the ~10-year time period from December 7, 1990 to December 31, 2000. Loop heights clearly show co-latitude dependence. The north-south asymmetry is evident in both loop heights and in open magnetic field strength.

Fisk [2002] has developed a solar wind model that predicts the observed inverse correlation between solar wind speed and inverse electron temperature. The theory also gives the latitudinal variation of the height of closed loops, the ratio of magnetic field strength to mass density in the loops, and the open magnetic flux. Using Fisk's solar wind model it will be possible to relate solar wind speed and O^{7+}/O^{6+} to loop heights and open magnetic flux over the latitudes sampled by Ulysses. Fig. 5.2 shows the results for the inferred variations of loop heights in U-I, assumed to be linearly related to electron temperature in loops [Gloeckler et al., 2002], and the open magnetic flux. There are both a co-latitude dependence of loop heights (or equivalently loop temperature) outside coronal holes and north-south asymmetries. *UFC* will permit measuring variations in open flux and loop heights as the PCHs appear again with the next solar minimum to show if, or how, the pattern is repeated and to evaluate this model.

6. ***Theme 4 The Interstellar Medium***

<u>*Research Objectives for FY2002-2004 from the Ulysses 2001 Senior Review Proposal*</u>

(1) Obtain better physical parameters and heavy element abundances of the Local Interstellar Cloud (LIC), providing improved constraints for galactic evolution models.

(2) Measure the LIC $^{22}Ne/^{20}Ne$ abundance to limit stellar evolution models.

(3) Determine the strength of the LIC magnetic field from pressure balance and the expected detection, or better estimates of the location, of the termination shock with Voyagers.

Table 5.1: *Topical list of 2004-2007 objectives - The 4D Heliosphere*
▪ Develop a global view of the 3-D heliosphere in the A<0 half of the Hale cycle. (2003-2008)
▪ Provide a test of the validity of models explaining the magnetic "flux deficit" using measurements in fast solar wind during the next solar minimum. (2005-2008)
▪ Investigate N-S asymmetries during *UFC* and compare them to asymmetries in U-I to understand the extent to which they are intrinsic and to develop constraints for the solar dynamo. (2006-2007)
--Continuing objectives from the 2001 Senior Review proposal
▪ Examine the solar wind over similar latitudes over a similar phase (declining) of the opposite polarity portion of the solar cycle. (2004-2005)
▪ Determine if the open magnetic flux is invariant in latitude and time throughout the solar cycle. (2004-2007)
▪ Characterize HCS tilt and dynamics as it rotates to lower latitudes. (2003-2004)

(4) Use Ulysses UV observations with SOHO measurements at 1 AU and Galileo, Cassini, and Voyager measurements to study solar rotational modulation of the Lyman-α brightness due to multiple scattering.

(5) Refine the gas:dust ratio of the LIC, to understand differences between in situ and optical observations.

(6) Provide accurate locations for new cosmic gamma ray bursts, enabling searches for optical counterparts.

(7) Monitor the activity of known magnetars and search for new magnetars, providing information on neutron stars with superstrong magnetic fields.

(8) Collaborate with the Swift GRB MIDEX mission in 2003/4, to verify and calibrate its burst localization capability at the start of the mission.

<u>Accomplishments in 2001-2003</u> and <u>Objectives for 2004-2005 and 2006-2007</u>

Gamma ray bursts and magnetars:

Cosmic gamma-ray bursts are the most luminous explosions in the Universe, allowing them to be detected to distances beyond the most distant quasars. They are a source of information on the formation rates of stars, the metallicities of early galaxies, the epoch at which the Universe re-ionized, and magnetars - neutron stars with the largest known magnetic field in the Universe. The most intense burst of non-solar gamma-rays ever detected was produced by a magnetar and studied with Ulysses [Hurley et al. 1999]; it had a profound effect on the terrestrial ionosphere [Inan et al. 1999].

Ulysses is the flagship of the 3rd Interplanetary Network of gamma-ray burst detectors, a collection of spacecraft which derives the precise positions of these objects by triangulation. The network detectors are isotropic so they detect strong bursts 10 times more often than other detectors and, in addition, monitor the entire sky for bursts from new sources. The network detected the most distant gamma-ray burst ever observed on January 31 2000, at a redshift of 4.5 [Andersen et al. 2000].

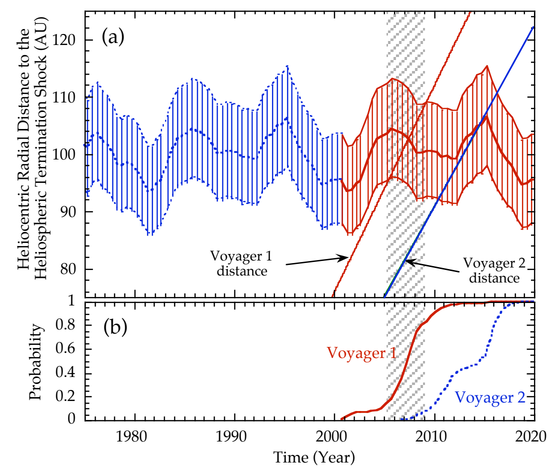

Figure 6.1 Location of the termination shock and probability of shock encounters by Voyagers 1 and 2 as a function of time. Shown in blue is the calculated mean and ±1-σ limits of the termination shock distance using IMP 8 solar wind speed and densities and the modified Baranov-Malama model. Shown in red is the calculated mean and ±1- σ limits of the termination shock distance using a repeat of the previous 20-year sequence [Izmodenov et al., 2002].

Parameters of the Local Interstellar Cloud:

Recently the heliosphere has entered a small, relatively dense, warm cloud — the Local Interstellar Cloud (LIC) — with consequences for Earth that are not yet fully understood [e.g., Lallement, 2001]. Ulysses continues to produce new information about LIC physical parameters, allowing better predictions of the location of the termination shock [Izmodenov et al., 2002]. Measurements of the chemical and isotopic composition further permit inferences about the history of the universe [Gloeckler and Geiss, 1996] and the ISM [Geiss et al., 2002]. Observations with Ulysses during *UFC* will allow us to attack the following problems.

Size and shape of the heliosphere:

The size and shape of the heliosphere and the injection of neutral gas into 1-10 AU are determined by physical characteristics of the LIC. Ulysses has the right orbit and instruments to infer properties of LIC atoms and pickup ions formed by ionization of the atoms. Ulysses/GAS provided the first direct measurement of interstellar helium. As a result, we know the relative velocity between the Sun and the LIC, the temperature of the LIC gas, and the density of interstellar neutral helium. SWICS has determined the H-density at the termination shock. Combining these results with models gives the best estimates of the gas and plasma density and the pressure in the LIC.

Ulysses high latitude measurements of neutral and pickup He and pickup H in *UFC*, combined with solar UV measurements from SOHO and ACE solar wind electron data, will map the latitude and solar cycle dependence of loss rates. This will improve the accuracy in the determination of physical properties of the LIC.

Heliospheric Termination Shock (TS):

Based largely on Ulysses' LIC parameters and 3D+time models, it is estimated that Voyager 1 will encounter the TS within five to six years (Fig. 6.1). Knowledge of the TS location allows better estimates of the magnitude of the interstellar magnetic field, currently only crudely constrained, and the ionization state of H and He in the LIC.

The state of the heliosphere when Voyager encounters the termination shock:

When Voyager 1 encounters the TS, it will mark an important milestone in heliospheric physics. To support that observation, the physical state of the heliosphere must be well documented in the years leading up to and following the encounter. Ulysses is currently the only spacecraft capable of characterizing the high-latitude heliosphere and its interaction with the LIC.

Variations in the LIC:

There is a possibility that the LIC may be inhomogeneous, with density variations of 10% to 15% over scales of ~100 AU. A good understanding of ionization loss rates and a long observation period will make it feasible to observe these inhomogeneities. This would fundamentally alter the traditional picture of a locally smooth LIC. *UFC* will extend the time series of LIC measurements to examine this possibility.

Isotopic composition of interstellar gas:

Interstellar $^3He/^4He$: Among the most significant Ulysses results has been the measurement of the isotopic helium ratio in the ISM [Gloeckler and Geiss, 1996], of fundamental importance for studies of galactic evolution. Pickup $^3He^+$ is difficult to detect so the accuracy of the measurement is statistics limited. With present technology $^3He^+$ can only be detected in fast solar wind, i.e. at high latitudes and near-minimum solar activity. Ulysses provides the only opportunity to make this measurement. *UFC*-FLS, when above ~30° latitude, will allow repeating the measurements of the interstellar $^3He/^4He$ ratio and thus improving its accuracy.

Interstellar $^{22}Ne/^{20}Ne$: Interstellar $^{22}Ne/^{20}Ne$ is **of** importance for understanding stellar evolution and recent galactic history. Only upper limits of this ratio have been obtained up to now. Interstellar $^{22}Ne/^{20}Ne$, unlike $^3He/^4He$, can only be measured in the slow solar wind using current technology. Thus, measurements of this important isotopic ratio will be made in early in *UFC*, up until Ulysses enters fast wind from the southern PCH.

Abundance of interstellar neutral heavy elements:

Ulysses pickup ion measurements showed that the metallicity (roughly the ratio of heavy elements to hydrogen) of the gas in and near the LIC is comparable to or lower than that of the Sun [Gloeckler and Geiss, 2001]. This was unexpected because supernovae should have enriched the metallicity. This may be explained by an excess infall of extragalactic material that is only moderately processed by stellar nucleosynthesis [Geiss et al, 2002]. This would also explain the lower than expected abundance of ^{18}O. Statistical uncertainties are too large to verify the model. Additional observations early in *UFC* will reduce these uncertainties. Only Ulysses is at sufficiently large distance to measure the heavy pickup ions from which the interstellar abundances are established**.**

Ion Cyclotron Waves:

The Ulysses/VHM/FGM detects ion cyclotron waves generated by the pickup of freshly ionized interstellar neutrals. These observations help to understand the wave-particle instability that generates the waves, their subsequent evolution as they are swept outward in the solar wind, and the role of the waves in coupling the pickup ions to the solar wind. The waves have only been observed at Ulysses. A technique has now been developed to better identify the waves. Data is now needed from 2003-2005, when Ulysses will be farther from the Sun. Continued observation by Ulysses in 2006-2007 will enable studying the dependence of wave occurrence and amplitude on heliographic latitude, and to infer properties of the incoming neutrals, their ionization length, the extent to which the waves are absorbed or reflected as the local gyro frequency decreases below the wave frequency, and the coupling between the quasi-periodic waves and the background HMF fluctuations or turbulence.

Dust (see also §4):

Interstellar dust detected with Ulysses/DUST implies larger particle sizes than deduced from astronomical methods. On the other hand, small grains are depleted due to filtering of electrically charged particles by the heliospheric bow shock region and the heliosphere itself. The gas-to-dust mass ratio of the interstellar medium derived from Ulysses measurements is a factor of 4-5 larger than derived from UV and optical extinction curves. This suggests that processes of grain mixing or the grain history are not understood or that there is an enhancement of interstellar dust in the local interstellar medium. Models for the dynamics of dust in the heliosphere [Landgraf 2000] explain the factor of 3 variation of the dust fluxes observed until 2000. They predict a rather constant dust flux until 2008. Ulysses/DUST observations in 2004-2007 will test the prediction, lead to better constraints on the gas-to-dust mass ratio, and improve understanding of dust in interstellar space.

Table 6.1: *Topical list of 2004-2007 objectives - The Interstellar Medium*
▪ Extend Ulysses' monitoring for gamma ray bursts and magnetars. (2004-2008)
▪ Determine properties of the Local Interstellar Cloud (LIC) such as neutral hydrogen density, etc., using the unique orbit of Ulysses to map latitude and solar cycle dependence of pickup ion parameters. (2004-2006)
▪ Investigate inhomogeneities of the LIC using Ulysses data to determine loss rates and temporal variations of interstellar H and He. (2004-2006)
▪ Characterize the high latitude heliosphere around the time of Voyager-1's (possible) encounter with the termination shock to provide maximum understanding of this unique event. (2005-2007)
▪ Improve the accuracy of the $^3He/^4He$ measurement in the ISM, with consequences for galactic evolution, missing mass in the universe, etc. (2005-2007)
▪ Constrain models for the enhancement of metallicity in the LIC by infall of extra-galactic materials, by extending observations of interstellar pickup N, O, and Ne in the slow solar wind (2003-2005).
▪ Obtain improved data on the ion cyclotron waves generated by pickup of freshly-ionized interstellar neutrals observed during radial magnetic field, to understand the wave-particle instabilities and coupling. (2003-2005)
▪ Measure gas:dust ratio in the LIC when A<0 and understand discrepancy with optical results. (2007-2008)
--Continuing objectives from the 2001 Senior Review proposal
▪ Measure the LIC $^{22}Ne/^{20}Ne$ abundance to limit stellar evolution models. (2003-2005)
▪ Determine the strength of the LIC magnetic field from pressure balance and the expected detection, or better estimates of the location, of the termination shock. (2003-2007)
▪ Use Ulysses observations with SOHO UV measurements at 1 AU and Galileo, Cassini, and Voyager measurements to study solar rotational modulation of the Ly-α brightness due to multiple scattering. (2004-2007)
▪ Operate in conjunction with the Swift GRB MIDEX mission in 2003/4, to verify and calibrate its burst localization capability at the start of the mission. (2003-2004)
▪ Establish ionization rates for various interstellar atoms inside the heliosphere as a function of latitude over the full solar cycle. These rates are required input parameters for modeling spatial distributions of interstellar neutrals and interplanetary Lyman-α emissions from SOHO and Ulysses. (2003-2006)